Diffuse Emission from the Galactic Plane and Unidentified EGRET Sources

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Abstract

Diffuse Galactic gamma-ray emission is produced in interactions of cosmic rays with gas and ambient photon fields and thus provides us with an indirect measurement of cosmic rays in various locations in the Galaxy. The diffuse gamma-ray continuum is more intense than expected both at energies below 200 keV and above 1 GeV. The existing models for the high-energy excess are reviewed in the light of recent TeV gamma-ray measurements of both diffuse emission and of discrete Galactic sources such as supernova remnants. I specifically discuss whether particular classes of Galactic objects are observable as EGRET gamma-ray sources, either by being found among the unidentified EGRET sources or by contributing to the diffuse emission as unresolved sources.

1. Introduction

The EGRET instrument aboard the Compton Gamma-Ray Observatory, CGRO, has observed the Galactic diffuse gamma-ray emission with unprecedented detail and accuracy. This emission is supposedly produced in interactions of Galactic cosmic rays, electrons and protons, with the interstellar gas and the interstellar radiation field. The spectral and spatial distribution of the diffuse radiation can be compared with models based on the locally observed spectra of cosmic rays and the Galactic distribution of interstellar gas and soft photon fields. Such studies indicate that while at photon energies below 1 GeV the observed intensity distribution in the Galactic plane is in accord with the model predictions, at higher energies above 1 GeV the observed intensity in the Galactic plane displays a GeV excess at a level of 60% compared with the predictions (Hunter et al. 1997). The diffuse Galactic emission around 100 keV is also in excess of predictions based on cosmic ray propagation models (Purcell et al. 1996; Valinia, Kinzer, and Marshall 2000).

EGRET has detected about 270 point sources, about two thirds of which have not been identified with objects observed in other frequency regimes (Hart-

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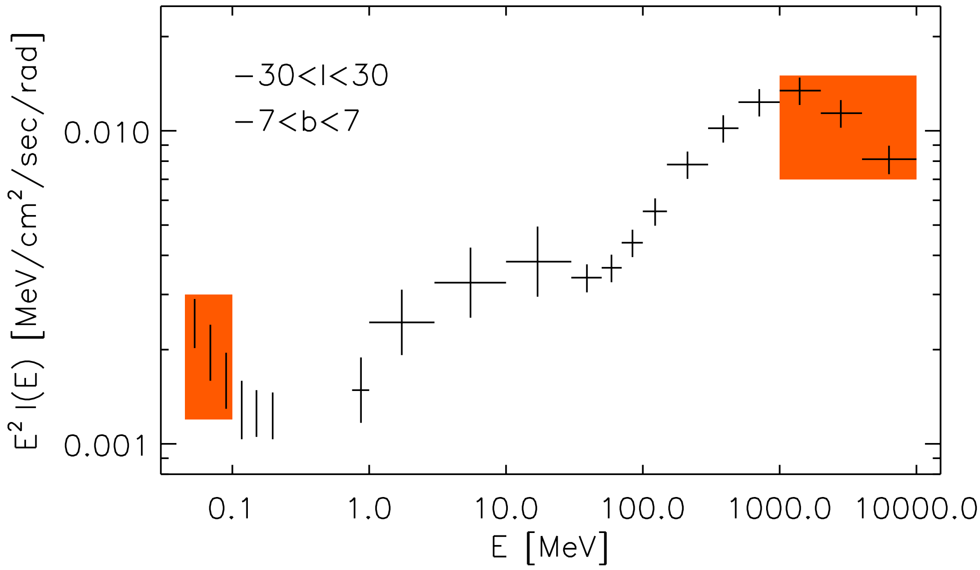

Fig. 1. The intensity spectrum of diffuse emission from the inner Galaxy. The data around 100 keV have been obtained with the OSSE experiment (Kinzer, Purcell, and Kurfess 1999), those in the MeV range result from observations with COMPTEL (Strong et al. 1996), and the GeV range spectrum has been derived from EGRET data after subtraction of known point sources (Hartman et al. 1999). The shaded regions indicate, at which gamma-ray energies the observed intensity exceeds that expected from interactions of cosmic rays with spectra similar to those observed in the solar vicinity.

man et al. 1999). It is possible, that the gamma-ray excesses are related to the unidentified point sources. This review will address the four following questions:
- What is the nature of the excesses in diffuse Galactic gamma-rays?
- What fraction of the diffuse Galactic emission is caused by unresolved sources?
- What is the nature of the unidentified EGRET sources?
- What is the relation between the gamma-ray excesses and the unidentified gamma-ray sources?

2. What is the nature of the excesses in diffuse Galactic gamma-rays?

The diffuse Galactic gamma-ray emission is most intense in the direction of the inner Galaxy. Figure 1 shows the observed intensity spectrum from that region. The shaded areas indicate, at which gamma-ray energies the observed intensity exceeds that expected from interactions of cosmic rays with spectra similar to those observed in the solar vicinity. The excess near 100 keV can, if truely diffuse, only be caused by either electron or proton bremsstrahlung. In

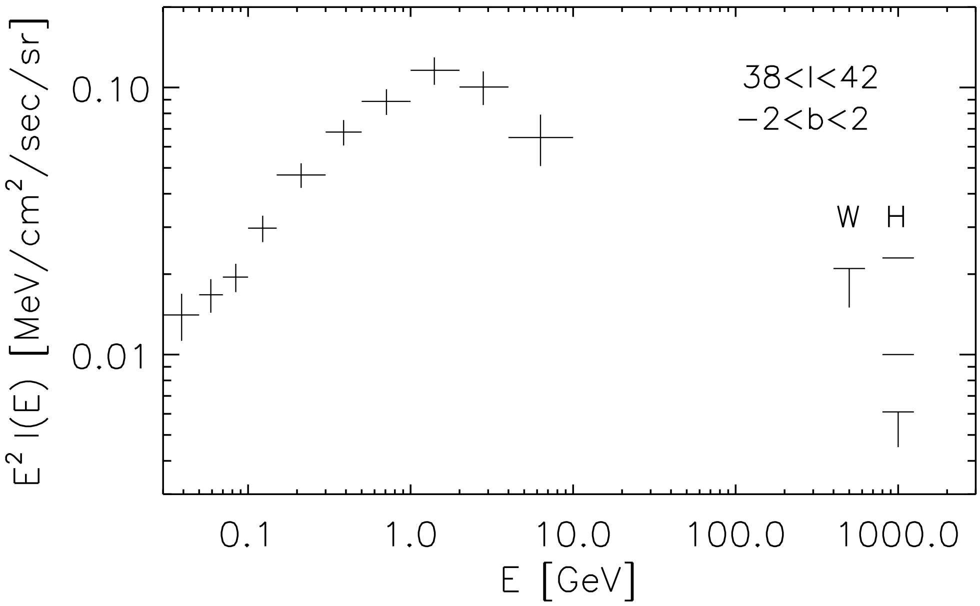

Fig. 2. The intensity spectrum of diffuse gamma-ray emission from a small region in the Galactic plane near $l = 40°$. The GeV-scale data have been obtained with the EGRET experiment. In the TeV range upper limits have been published by the Whipple team ("W", LeBohec et al. 2000) and the HEGRA collaboration ("H", Aharonian et al. 2001), for which three limits are given depending on whether all gamma-ray like events are considered, or a high-latitude observation or the $|b| \geq 2°$ data are used for background estimation.

both cases the radiation efficiency would be very low, and therefore a very high cosmic-ray source power in excess of, e.g., that supplied by supernovae would be needed to sustain the particle population (Skibo et al. 1996; Valinia & Marshall 1998). In addition, proton bremsstrahlung as the main emission mechanism of the observed low-energy gamma rays seems to be in conflict with the observational limits on nuclear line and pion-decay continuum emission (Pohl 1998). The point source contamination of the Galactic 100 keV radiation is unknown, but will be determined with INTEGRAL in the near future.

The GeV excess is unlikely to be an instrumental effect, in particular because the Crab spectrum is observed to be a single power-law with no indication of an excess at GeV energies. The extent of the GeV excess towards higher energies is not well constrained by the existing limits on diffuse TeV-scale emission, which are shown in Figure 2. The EGRET data displayed in that figure are not corrected for the effects of the point-spread function, so that the true intensity at energies below around 300 MeV is probably somewhat higher than indicated here. An extrapolation of the spectrum at a GeV and higher, at which energies

Table 1. Results of a linear correlation analysis of the observed intensity versus that expected for the diffuse Galactic emission at high latitudes (Sreekumar et al. 1998). The residual, A, is the intensity in units of (10^{-6} cm^{-2} sec^{-1} sr^{-1}) of the presumably extragalactic emission that remains after extrapolating to zero Galactic radiation, whereas the slope, B, is the scale factor needed to match model and observation of the Galactic emission. The large values of B for energies beyond 1 GeV indicate a GeV excess similar to that in the Galactic plane.

Energy range in MeV	Residual A	Slope B
30-50	24.0±6.4	1.14
50-70	13.1±1.9	1.04
70-100	7.8±0.27	1.09
100-150	5.5±0.20	1.05
150-300	5.3±0.21	0.97
300-500	1.9±0.10	0.97
500-1000	1.3±0.07	1.09
1000-2000	0.67±0.036	1.34
2000-4000	0.41±0.028	1.85
4000-10000	0.19±0.017	1.56

the point-spread function is a minor concern, is not in conflict with the upper limits in the TeV range. The TeV data do, however, constrain models of the GeV excess which invoke a hard spectral component arising, e.g., from inverse Compton (IC) scattering of high-energy electrons accelerated in supernova remnants (Pohl & Esposito 1998). The available X-ray data from young remnants indicate that electrons are accelerated to around 10 TeV, beyond which the spectrums shows a strong depression or cut-off (Reynolds & Keohane 1999), implying corresponding turn-overs in the IC spectra around 100 GeV, so that the present TeV scale data are not in conflict with the hard IC interpretation of the GeV excess.

The original analysis that led to the detection of the GeV excess concentrated on the Galactic plane, for the Galactic emission is strongest in that region. One should note that also at high latitudes a corresponding excess is visible. Sreekumar et al. (1998) have linearly correlated the observed intensity with that predicted by a cosmic-ray propagation model with a view to determine the extragalactic background by extrapolating to zero Galactic emission. Table 1 gives the slopes of that correlation at different energies. They are around unity for gamma-ray energies below 1 GeV, but vary between 1.35 and 1.85 above 1 GeV, indicating the existence of a GeV excess of roughly the same magnitude as in the Galactic plane.

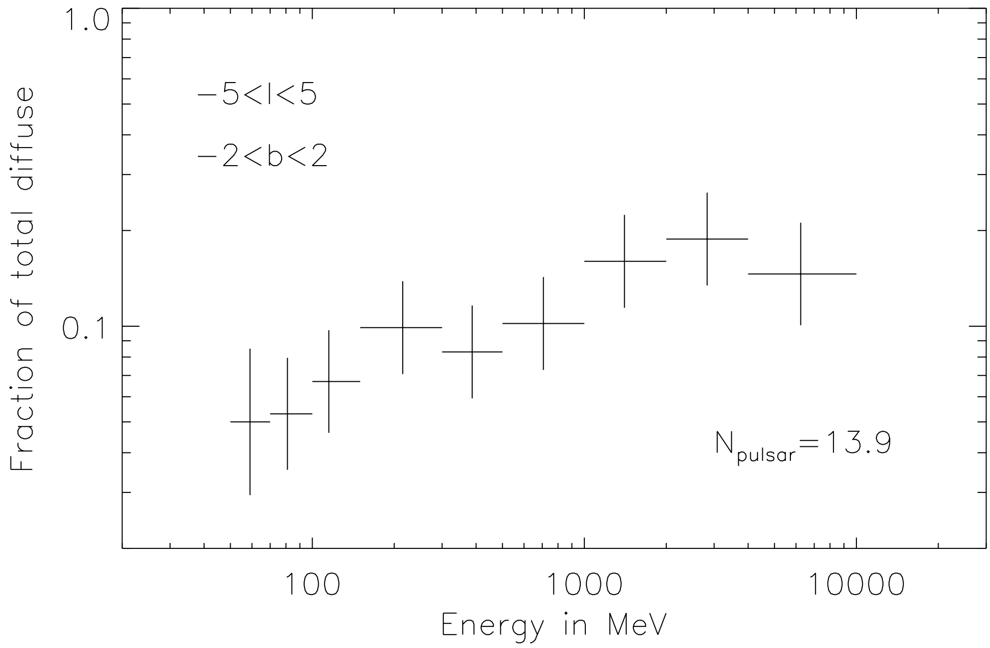

Fig. 3. The intensity spectrum of unresolved pulsars shown in units of the total observed diffuse gamma-ray emission (Pohl et al. 1997). The intensity scales linearly with the number of observable pulsars, which would be 13.9 for this plot.

3. Unresolved sources in the diffuse gamma-ray emission

Estimates of the contribution of unresolved sources have a firm basis only if the flux level of at least a few members of the source class in question is known. In the gamma-ray regime the only class of Galactic sources with that property is pulsars. Emission models or just the luminosities of the observed sources can then be used to estimate the gamma-ray intensity produced by the total population of sources. Based on the observed spectra of six EGRET pulsars Pohl et al. (1997) have fitted an empirical luminosity function at different energies and were thus able to estimate the intensity spectrum produced by unresolved pulsars. The absolute intensity levels scales linearly with the number of pulsar observable as point sources (not necessarily as pulsars). Figure 3 shows the fraction of the total diffuse emission from the Galactic center region that would be produced by unresolved pulsars. Pulsars would indeed most significantly contribute at energies of a few GeV. In the Galactic center direction, where the pulsar contribution would be strongest, they would provide nearly 20% of the observed intensity above 1 GeV for 14 observable pulsars. In other directions the contribution would be less than that. Figure 4 shows the latitude distribution of the intensity of unresolved

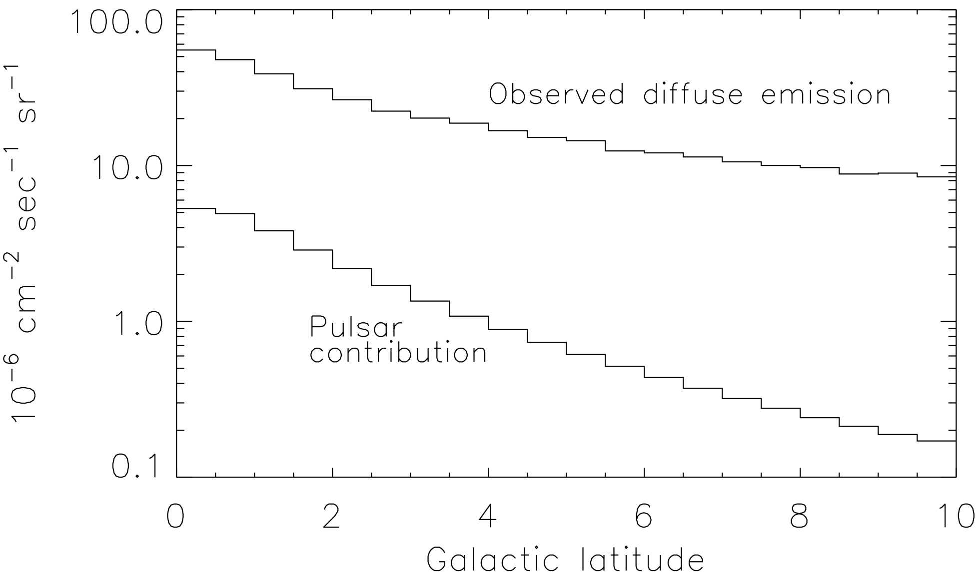

Fig. 4. The longitude-averaged latitude distribution of the intensity provided by unresolved pulsars shown in comparison with that of the observed diffuse emission. The absolute intensity corresponds to 13.9 observable pulsars as in Fig.3.

pulsars averaged over Galactic longitude. To be noted from the figure is that on average the pulsar contribution to the diffuse Galactic emission is below 10% and that the predicted latitude distribution differs from that of the observed diffuse emission, so that at higher latitudes the pulsar contribution becomes negligible. Thus unresolved pulsars cannot explain the GeV excess. McLaughlin and Cordes (2000) have used a spin-down model to estimate the pulsar contribution to the diffuse Galactic emission above 100 MeV and the number of pulsars among the EGRET unidentified sources. They find that about twenty unidentified sources might be pulsars. Nevertheless, pulsars would not significantly contribute to the diffuse Galactic gamma-ray emission. These results are completely in line with those of Pohl et al. (1997), though the methods used are different.

4. The nature of unidentified EGRET sources

In this review we are mainly interested in Galactic sources. So how do we know a source is galactic, if it is unidentified? Of course we can't tell for the individual source. Intriguing though its association with Cygnus OB2 is, the one and only unidentified TeV gamma-ray source could be a background object, provided the indications of extended emission prove unsubstantiated (Aharonian et al. 2002). If many unidentified sources are present, like 170 in case of EGRET, one can use their spatial distribution to infer how many of them have a Galactic origin. Approximately 100 EGRET sources appear to be Galactic on this ground. This result depends somewhat on the assumed spatial distribution and on the luminosity function of the sources in question. Consequently the uncertainty in that figure is slightly higher than the Poissonian error margin of ± 10.

A many authors have attempted to infer the nature of the unidentified Galactic sources by studying the spectra (Merck et al. 1996; Zhang & Cheng 1998), the variability properties (McLaughlin et al. 1996), or spatial correlations with known source classes such as supernova remnants (SNR) or OB associations (Sturner & Dermer 1995; Kaaret & Cottam 1996,; Romero et al. 1999). However, care must be exercised in the analysis of EGRET data, for a number of systematic effects influence the population studies. Flat-spectrum sources are more easily found in regions of a high background intensity, i.e. in the Galactic plane. The backward-folding of data in the EGRET standard analysis, as opposed to the forward-folding of a sky model through the instrument response, can cause a "false" variability of sources in the Galactic plane. Correlation studies with known classes of objects are hampered by the large number of objects both in the source class in question and in the typical EGRET error box for a Galactic plane source. Nevertheless, few of the low-latitude unidentified source seem to have a hard gamma-ray spectrum with index $\gamma \leq 2.0$.

It may be useful then to calculate what one might expect to see from different source classes. We have already discussed the case of pulsars, for which one would expect a constant flux and a rather wide latitude distribution. Only a few of the unidentified EGRET sources display the hard spectrum that appears typical of the identified pulsars. It is possible, though, that one observes pulsars by their off-beam emission, which in the polar-cap model would have a soft spectrum with low luminosity (Harding & Zhang 2001). Such off-beam gamma-ray pulsars would be candidates for the population of unidentified EGRET sources that is apparently associated with Gould's Belt (Grenier 2000; Gehrels et al. 2000). Off-beam emission is not expected in outer-gap models (Yadigaroglu & Romani 1995; Cheng & Zhang 1998), which predict that most of the unidentified EGRET sources in the Galactic plane are radio-quiet pulsars.

SNR should also display a constant flux, but would have a narrow latitude distribution. No EGRET source has been unambiguously identified with a SNR to date, but three SNR have been observed as sources of TeV gamma-rays. It is difficult to extrapolate the gamma-ray spectrum of SNR from the TeV band to GeV energies, for the relative importance of the contributions from π^0-decay, non-thermal bremsstrahlung and IC scattering are a priori unknown. If a non-thermal spectral component exists at X-ray energies, which most likely would be

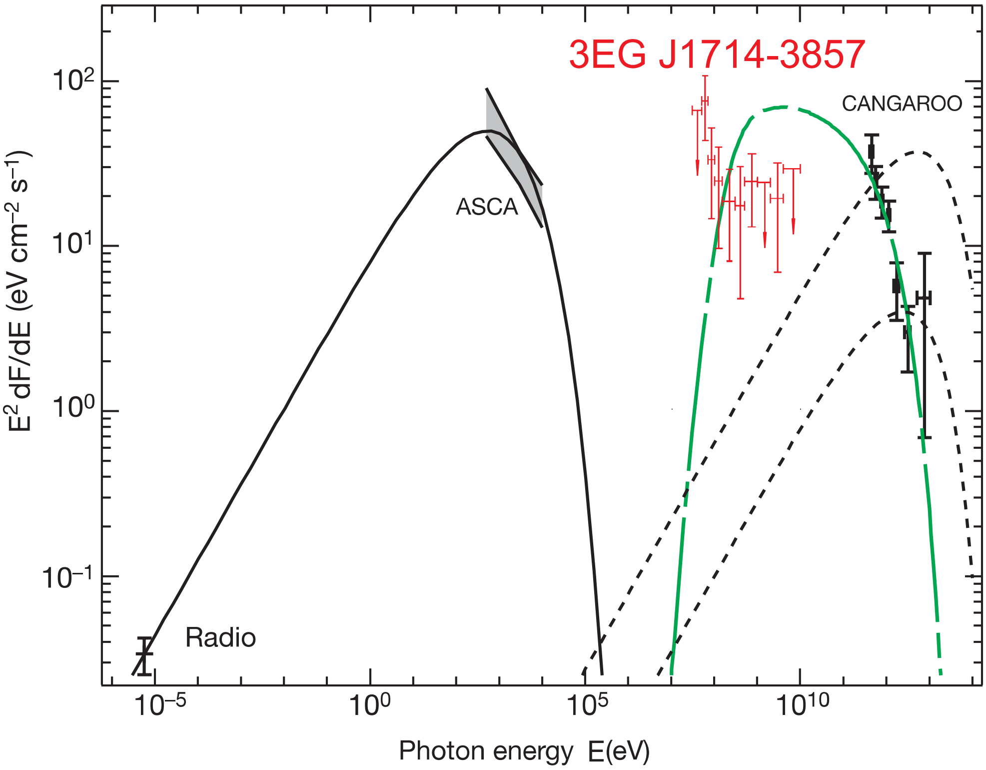

Fig. 5. The multi-band spectrum of RX J1713.7−3946 from Enomoto et al. (2002), revised by Reimer & Pohl (2002) to include the γ-ray spectrum of 3EG J1714−3857, is shown in comparison with emission models presented in the former publication. The solid line indicates synchrotron emission, and the dashed lines are the corresponding IC spectra based on the microwave background and the ambient far-infrared photon field for two sets of parameters, both of which would violate the observed TeV γ-ray spectrum. The grey long-short-dashed line shows the π^0-decay spectrum, which significantly exceeds the total observed emission by a factor of three.

synchrotron emission of extremely high-energy electrons, the flux and the spectral form of the IC emission depends only on the magnetic field strength at the rim of the remnant and in its interior. The flux of gamma-rays from π^0-decay and from bremsstrahlung cannot be easily estimated because the density of both the non-thermal particles and the ambient gas is unknown.

It is generally difficult to infer the main radiation mechanism in the TeV band. In the case of SN 1006 the dominant process is probably inverse Compton scattering on account of the low-density environment in which the remnant resides. The situation is less clear for RX J1713.7−3946 and Cas A, for which, however, there is also no clear evidence for hadronic TeV-scale emission. A good example of the dilemma is RX J1713.7−3946, whose spectrum is shown in Fig.5. Recent measurements with the CANGAROO II telescope have indicated that the TeV-scale gamma-ray spectrum of RX J1713.7−3946 can be well represented by a single power-law with index $\alpha \simeq 2.8$ between 400 GeV and 8 TeV (Enomoto et al. 2002). The authors argue that the multi-band spectrum from radio frequencies to TeV gamma-ray energies cannot be explained as the composite of a synchrotron and an IC component emitted by a population of relativistic electrons. It is then claimed that the spectrum of the high-energy emission is a good match to that predicted by pion decay. Hence RX J1713.7−3946 would provide observational evidence that protons are accelerated in SNR to at least TeV energies.

Then Reimer & Pohl (2002) have reanalyzed the multi-band spectrum of RX J1713.7−3946 under the constraint that the GeV-scale emission observed from the closely located EGRET source 3EG J1714−3857 is taken into account as either being associated with the SNR or as an upper limit to the emission of the SNR. For both cases they find that a pion-decay origin of the observed TeV-scale gamma-ray emission of RX J1713.7−3946 is highly unlikely, contrary to the previous claim. The paucity of spatially resolved radio and X-ray data suggests that answering the question whether or not IC scattering can be responsible for the observed TeV-scale gamma-ray emission of RX J1713.7−3946, whatever the origin of the EGRET source 3EG J1714−3857, requires a better knowledge of the synchrotron spectrum of the SNR than available to date.

5. The relation between the gamma-ray excesses and the unidentified EGRET sources

Whatever the dominant emission process of the TeV-scale emission from Cas A and RX J1713.7−3946, the relative sensitivities of EGRET and the present generation of atmospheric Čerenkov telescopes in conjunction with the expected form of the gamma-ray spectrum from SNR indicate that either only a few SNR can be among the EGRET unidentified sources or many SNR do not accelerate cosmic rays to more than 10 TeV, in which case the gamma-ray spectra would display a turn-over near 100 GeV.

But what about unresolved SNR, would they contribute to the diffuse Galactic gamma-ray emission? The expected gamma-ray spectrum of unresolved SNR would be substantially harder than that of the diffuse Galactic emission, because the energy-dependent escape of cosmic rays from the Galaxy has no effect inside the sources. Unresolved SNR would therefore most significantly contribute in the TeV band (Berezhko & Völk 2000), but presumably very little at GeV energies. This is in accord with the energy-dependence of the Boron-to-Carbon ratio observed in the solar vicinity. If cosmic rays would predominantly interact with gas while still residing in their sources, essentially all of the Boron production would also occur within the remnants, and the Boron-to-Carbon ratio would therefore have to be flat, contrary to the measured behaviour up to 20 GeV/nuc. Thus unresolved SNR contribute little to the diffuse Galactic GeV-scale emission and in particular can not be the source of the GeV excess.

If unresolved SNR do not account for the GeV excess, what are the consequences for the emission of electrons that have already been released by the remnant? One of the possible explanations for the GeV excess is the Swiss Cheese Model (Pohl & Esposito 1998; Strong, Moskalenko, and Reimer 2000), which argues that high-energy electrons suffer energy losses so rapidly, that they do not propagate very far from their sources. Consequently the spatial distribution of these electrons would be inhomogeneous and the locally observed spectrum would not be representative for the electron spectra at other places in the Galaxy, where they could be substantially harder. The correspondingly hard IC gamma-ray spectrum, so the idea, would explain much of the GeV excess.

In these calculations it was assumed that the electrons are instantly released when accelerated, and that the electron acceleration would proceed for 10^4 to 10^5 years in a typical remnant. GeV-scale IC emission is produced by TeV-scale electrons, which have a radiative lifetime of around 10^5 years. During that time the average electron will propagate about 300 pc, so that the SNR would be embedded in a cloud of high-energy electrons with radius 300 pc. Seen from a distance, say 5 kpc away, the corresponding enhancement in IC intensity would have a radius of about 3°. The enhancements at distances less than 5 kpc from us would not be point sources for EGRET and, consequently, would be subsumed with the diffuse Galactic emission as originally assumed.

But is that realistic? We know that cosmic rays are not instantly released by the remnants, because the scattering mean free path of cosmic rays is much smaller near the rims of the remnant than it is in interstellar space. After 10^5 years the SNR has expanded to a radius of 50−100 pc, depending on the density of gas in its environment, corresponding to approximately $0.5° - 1°$ when seen from 5 kpc away. Upstream of the (parallel) SNR shock, in the precursor, the density of high-energy electrons falls off on a scale $\delta r \simeq \kappa/V$, where κ is the diffusion coefficient and V is the shock velocity. In the Sedov case $V \simeq 300$ km/sec after 10^5 years and $\kappa = \eta\kappa_{\rm B}$ will be many orders of magnitude larger than the Bohm diffusion coefficient, $\kappa_{\rm B}$, i.e. $\eta \gg 1$. Then for TeV electrons in a typical magnetic field of $B = 5\ \mu$G we obtain $\delta r \simeq \eta\, 0.1$ pc$\gg$ 1 pc. We do not know the value of η, but it is probably very large, so that after 10^5 years the enhancement in the density of high-energy electrons will have a radius at some value between the size of the remnant, that is 50−100 pc, and the radius calculated under the assumption of instantaneous release, approximately 300 pc.

What are the consequences? First, the corresponding enhancement in the IC intensity would still have a radius of around 1° when 5 kpc away, so that nearby structures, e.g. those at Galactic latitudes of 5° and higher, would still not appear as point sources in the EGRET data. Second, the smaller the region of enhanced electron flux around the location of a supernova is, the larger are the temporal fluctuations in the electron flux at a given location, which actually enhances the compatibility of the locally observed high-energy electron spectrum with the electron source spectrum that is required in the Swiss Cheese Model. All in all, the non-detection of individual SNR in the EGRET data does not seem to be in a strong conflict with that model of the GeV excess.

We have seen that only few of the Galactic unidentified sources will be pulsars and SNR. That leaves us with still ∼100 unidentified sources. Is the GeV excess perhaps caused by an unknown class of Galactic gamma-ray emitters, which we also find among the EGRET unidentified sources? Torres et al. (2001) have analyzed 40 low-latitude unidentified sources which are not positionally coincident with any known class of potential gamma-ray emitters. Surprisingly, many of them appear to be variable and on average these sources have a soft spectrum. What we observe is apparently a new class of gamma-ray emitters. Obviously, unresolved sources of that class cannot contribute to the GeV excess on account of the soft spectrum. We can calculate a lower limit for their luminosity $L \geq 10^{34}$ erg/sec, though, by arguing that they should not overproduce the diffuse emission around 100 MeV.

6. Summary

In this paper I have discussed the relation between unidentified EGRET sources and the diffuse Galactic gamma-ray emission with emphasis on the GeV excess. The results can be summarized as follows:

- About 100 of the EGRET unidentified sources seem to be galactic.
- Only a small fraction of them will be pulsars and SNR.
- The majority of them apparently belongs to other, new classes of gamma-ray emitters.
- Diffuse gamma-ray excesses have been observed at energies of around 100 keV and at a few GeV.
- The GeV excess is probably not caused by unresolved point sources.
- Hard IC models of the GeV excess are not in a serious conflict with the non-detection of SNR or SNR halos by EGRET.

7. Acknowledgements

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